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A Modeling Analysis Program for the JPL Table Mountain Io Sodium Cloud Data

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16. Abstract

Progress and achievements in the first year are discussed in three main areas: (1) review and assessment of the massive JPL Table Mountain Io sodium cloud data set, (2) formulation and execution of a plan to perform further processing of this data set, and (3) initiation of modeling activities. The complete 1976-79 and 1981 data sets have been reviewed. Particular emphasis has been placed on the superior 1981 Region B/C images which provide a rich base of information for studying the structure and escape of gases from Io as well as possible east-west and magnetic longitudinal asymmetries in the plasma torus. A data processing plan has been developed and has been undertaken by the Multimission Image Processing Laboratory (MIPL) of JPL for the purpose of providing a more refined and complete data set for our modeling studies in the second year. Modeling priorities are formulated and initial progress in achieving these goals is reported.

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I. Introduction

The goals of this project are to provide physical insight into the local structure of Io's atmosphere, the manner by which gases escape the gravitational well of the satellite and produce neutral clouds in the circumplanetary space, the nature of east-west and possible magnetic longitude asymmetries in the plasma torus, and the stability or variability of both the neutral gas clouds and the plasma torus over a several year time period. These goals are pursued in this AER/JPL collaborative effort by studying and modeling the spatial morphology, intensity, and space-time variability of the Io sodium cloud as preserved in the JPL Table Mountain Io sodium cloud data set, the most complete of the Io sodium cloud data sets currently available. This data set documents the 2-D spatial morphology of the D-line emission intensities of the cloud on the sky plane as a function of both Io geometric phase angle and the magnetic longitude of Io in the System III coordinate frame over a time period from 1976 to 1981. Highly developed and unique models for the Io sodium cloud at AER provide the key tool for extracting physical insights from this data set.

Progress in the first year can be divided into three areas: (1) review and assessment of the JPL Table Mountain Io sodium cloud data set, (2) prioritization, preliminary preparation, and initiation of new data processing activities for image and slit data, and (3) formulation, preliminary preparations, and initiation of modeling activities. These three areas naturally follow in a one-two-three order. Primary emphasis in the first year has thus been to complete the objectives of the first area, to make substantial progress in the second area, and to initiate the third area as data that has undergone more detailed processing becomes available. The discussion of first year progress and achievements given below is divided into these three areas. A paper discussing the potential and progress of this project was presented last year at the AAS/DPS meeting (Goldberg and Smyth, 1984).

II. Review and Assessment of the JPL Data Set

1. Overview

The observing program that acquired the JPL Table Mountain Io sodium cloud data began in 1974 and continued through 1981, with useful measurements obtained each year except 1980. The observing chronology for these measurements is summarized in Table 1. Prior to 1976, observations were made only with a single slit centered on Io. Results of these observations were reported earlier by Bergstralh et al. (1975, 1977).

Imaging observations of the Io sodium cloud have been obtained at the JPL Table Mountain Observatory since 1976. This imaging program has evolved through improvements in detectors, observing techniques, and data analysis methods. Major developments in all three of these areas in 1981 resulted in a quantum jump in both the quantity and quality of data taken. The proposed modeling analysis will focus primarily on Region B/C images from the 1981 data set, with further but selective studies of the Region B/C images in the 1976-1979 data set also included. The number of observations acquired in the 1976-1981 period is summarized in Table 2. The single slit measurements and two-dimensional images of Region A in Table 2 are also important in this modeling analysis program. They provide the information to properly calibrate the Region B/C images and also to directly link the 1976-1981 observations to the earlier 1974-1976 observations. This link is important in assessing the temporal variability/stability of the sodium cloud over the eight year period.

2. 1981 Region B/C Images

The 263 images obtained during the 1981 apparition for Region B/C were acquired over 14 nights. Images each night were recorded with an integration time of approximately 10 minutes. Three consecutive images were usually added to improve signal to noise. These added images provide a time-averaged picture of the sodium cloud over an Io phase angle interval of about 4° and an Io System III magnetic longitudinal interval of about 14° and, therefore, approximate reasonably well instantaneous snapshots of the Io sodium cloud. The UT dates and time intervals for these observations during the 14 nights are given in Table 3. Also included in Table 3 are the values of the geocentric phase angles and system III magnetic longitudes of Io for the start and end times of each evening. This angular information is important in

TABLE 1

TABLE MOUNTAIN OBSERVING CHRONOLOGY: IO SODIUM PROGRAM

Observing Technique	Date	Detector	Typical Exposure Time	Measurement
Single Slit on Io	1974-76	Wampler Scanner	1 hr.	Integrated Brightness near Io
	1976-79	SIT Vidicon	40 min.	Brightness N/S along Slit
	1981	ISIT Vidicon	3 min.	Brightness N/S along Slit
Multislits 9 arc-secs E & W of Io	1976	Wampler Scanner	1 hr.	Brightness Ratios
	1976-78	SIT Vidicon	1 hr.	
2-D Imaging of Region B	1976-79	SIT Vidicon	2-3 hrs.	2-D Brightness Distributions, Cloud Dynamics, 3-D Morphology
	1981	ISIT Vidicon	10 min.	
2-D Imaging of Region A	1981	ISIT Vidicon	3 min.	2-D Brightness Distributions, Cloud Dynamics, 3-D Morphology

NOTE: All measurements were made at the coudé focus of the 24-inch (61 cm) telescope. The spatial scale and spectral dispersion remained constant throughout.

Table 2

JPL Table Mountain Io Sodium Cloud Data: Number of 1976-1981 Measurements Acquired

Year(s) of Observation	single slit (Region A)	multi-slit (Region B)	2-D images (Region B/C)	2-D images (Region A)
1976-1979	31	9	39	-
1981	56	-	263	153

Table 3

1981 Region B/C Images: Observing Chronology

Date of Observations	Start Conditions: Time (UT)	Start Conditions: Io Phase Angle (deg)	Start Conditions: Magnetic Longitude of Io† (deg)	End Conditions: Time (UT)	End Conditions: Io Phase Angle (deg)	End Conditions: Magnetic Longitude of Io† (deg)
25 March	7:03	25.2	275.3	8:23	36.5	312.7
5 April	5:18	89.6	365.0	7:40	109.5	70.9
6 April	4:33	287.3	290.7	5:52	298.5	327.3
6 April	6:38	305.1	348.5	7:44	314.4	19.1
28 April	4:21	84.0	200.2	8:50	121.9	324.9
29 April	3:18	279.2	117.5	7:15	312.9	227.1
4 May	3:10	215.4	209.2	9:43	271.4	30.8
5 May	3:17	60.0	159.4	9:25	111.7	330.2
6 May	3:07	262.5	101.4	8:27	307.9	249.5
12 May	3:15	44.5	147.5	8:56	92.4	305.7
13 May	3:20	248.9	96.6	8:51	296.0	249.6
4 June	3:34	47.2	377.3	5:48	66.0	79.5
5 June	3:38	251.7	325.6	4:07	255.8	339.1
5 June	5:27	267.2	16.0	5:55	271.1	29.0
6 June	3:48	95.8	278.0	5:56	113.9	337.3
14 June	3:38	282.7	208.4	5:20	297.1	255.7

†System III (1965)

classifying the spatial morphology of Region B/C and is presented in graphical form in Figure 1. Representative images at the locations indicated by the symbols A, B, and C in Figure 1, are shown in Figure 2.

In Figure 1, the angular coverage in System III magnetic longitude of Io is excellent. The angular coverage in Io geocentric phase angle is only deficient near 0° and 180° where observational conditions are poor because of the high background light levels reflected by Jupiter's disk. As can be seen in Figure 1, there are three pairs of successive observations (each separated by a 32 day time interval) where the coverage in both angles is essentially identical. These three pairs provide an excellent test of the temporal variability/stability of the Io sodium cloud.

Most of the 263 images have been processed (prior to this project) only preliminarily to remove background signal. Images acquired on May 4, 5, 12 and 13 and June 4 had, however, undergone further processing to remove the instrumental response function and to normalize the image intensity. Because of this, images acquired on May 4, 5, 12 and 13 were chosen as a representative sample (42%, or 110 images) for a more thorough review. Magnetic tapes containing these images were received at AER and contour plots of many of these images were prepared (see examples in Figure 2) and used in this review (see the second progress report for details). In this review, the spatial morphology of the Region B/C sodium cloud images were divided into two main components: (1) the bright forward cloud that precedes Io and is located primarily inside of the satellite orbit, and (2) the dimmer directional feature that trails behind Io and is located primarily outside of the satellite orbit. An east-west orbital asymmetry in the forward cloud, noted first by Goldberg et al. (1978, 1980) and attributed by Smyth (1979, 1983) to the effects of solar radiation pressure, was noted. Directional features, first discovered by Pilcher [see Hartline (1980); Pilcher et al. (1984)], were also evident, and their north-south inclinations (see Figure 2) were consistent (except for the May 4 data where spatial distortions near Io have yet to be more accurately assessed) with the correlation with Io's magnetic longitude determined by Pilcher et al. (1984) and shown in Figure 3. The review also indicated that for quantitative modeling purposes further image processing refinements were required to more accurately remove the background signal and especially distortions in the spatial brightness near Io introduced by continuum light scattered by Io.

1981 IO SODIUM CLOUD DATA FROM TABLE MOUNTAIN OBSERVATORY

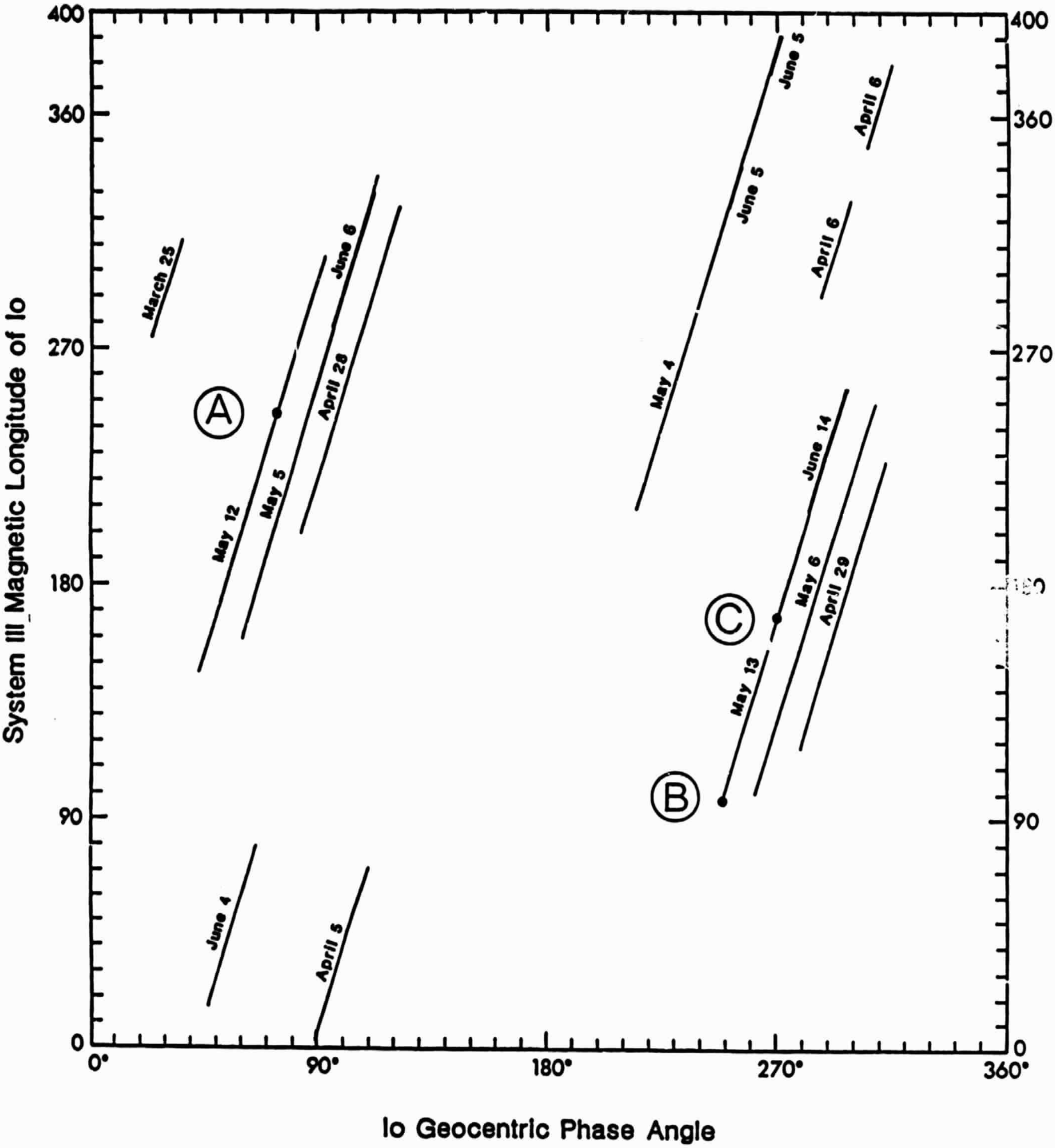

Figure 1. Observing Parameters for 1981 Io Sodium Cloud Images.

The angular coverage for the Io geocentric phase angle and the System III magnetic longitude of Io over which Region B/C images were recorded in the JPL Table Mountain Data Set is indicated for all 14 nights of observations. Three particular images denoted by A, B and C are discussed in the text and shown in Figure 2.

IO SODIUM CLOUD 1981

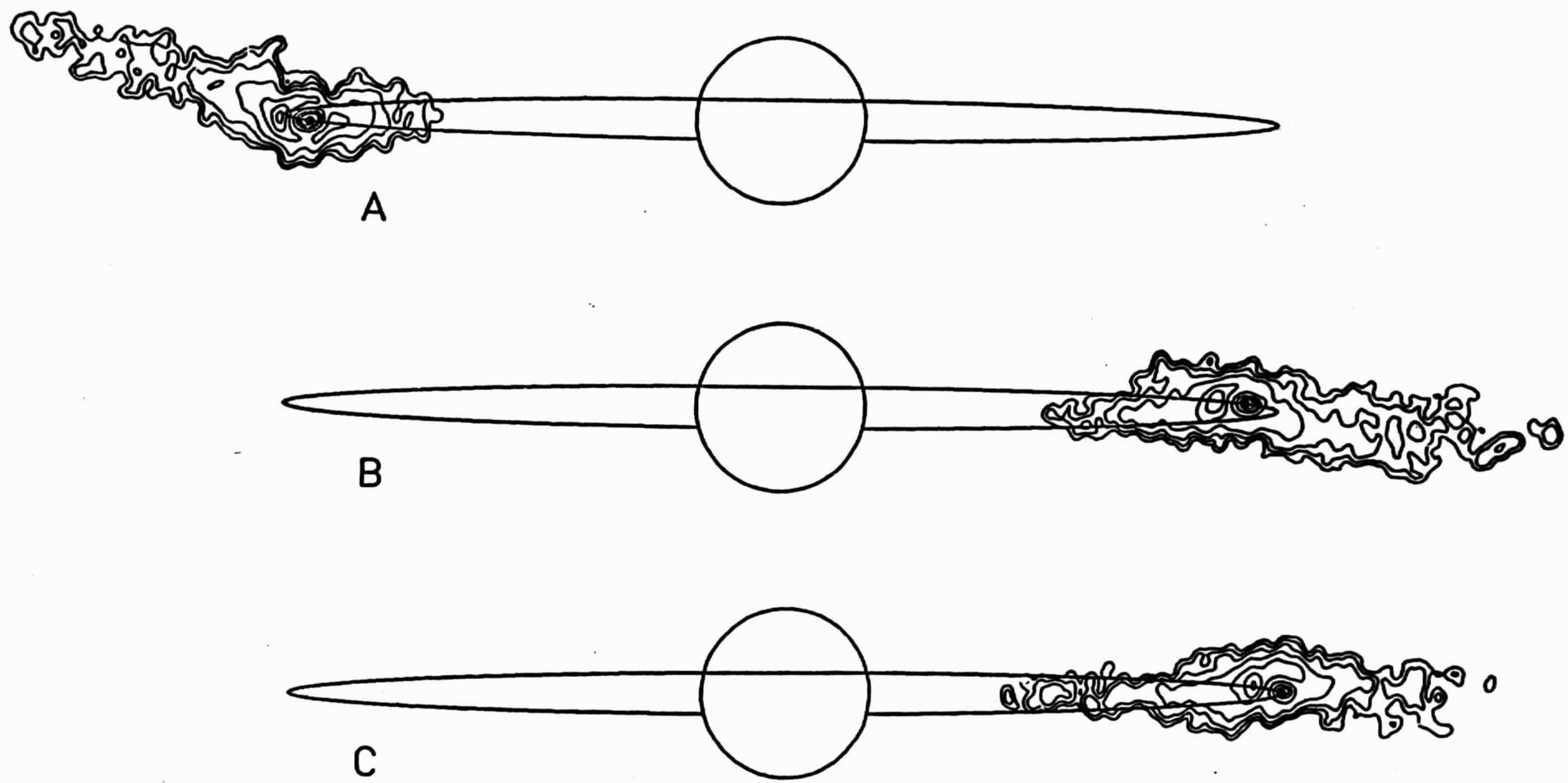

Figure 2. 1981 Region B/C Images of the Io Sodium Cloud.

The three images identified by A, B, C are part of the larger data set of images obtained from the Table Mountain Observatory. The observing parameters of these three images are indicated in Figure 1.

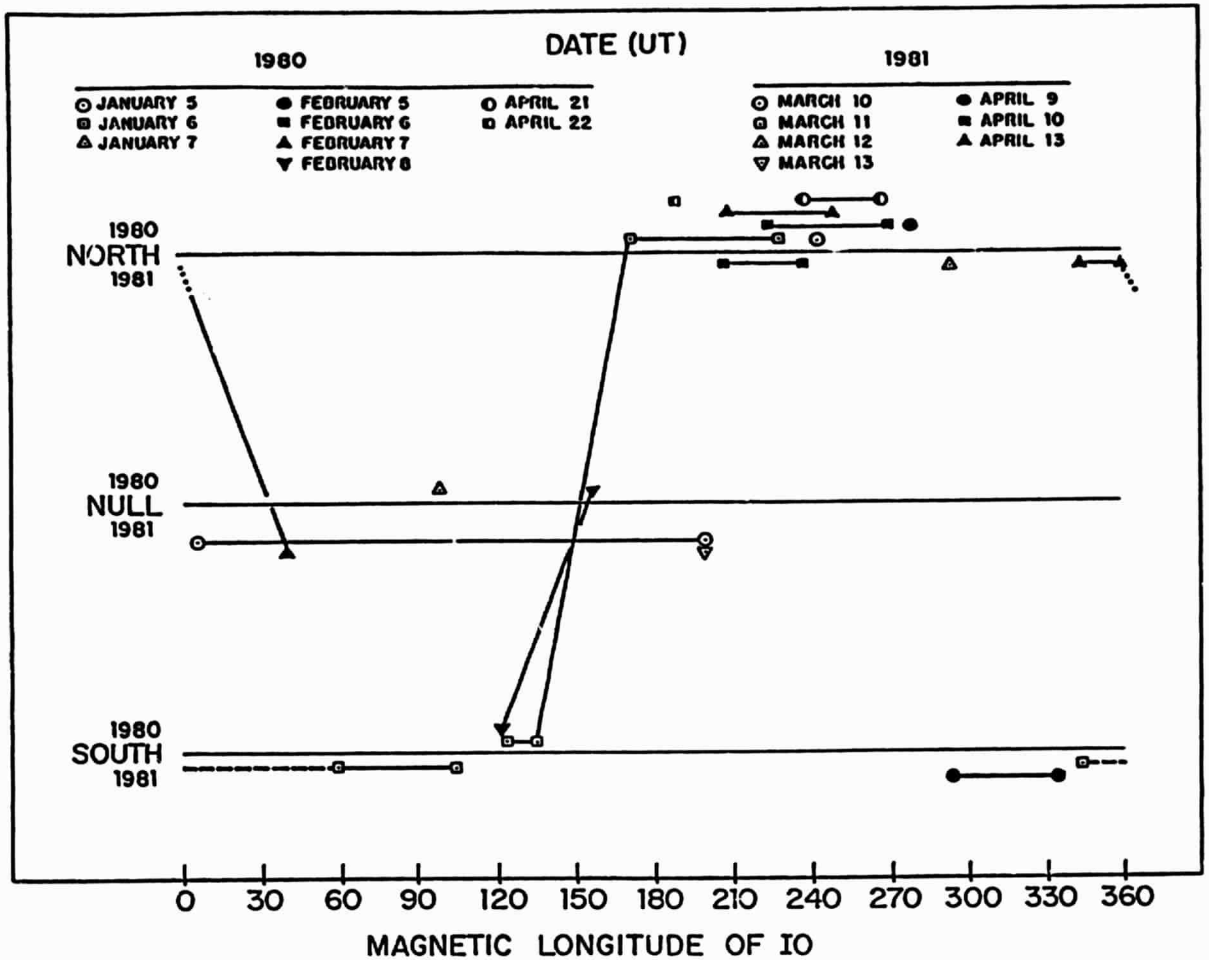

Figure 3. Classification of Directional Features of Pilcher et al. (1984) as a Function of Io's Magnetic Longitude at the Time of the Observations.

Observed northward features are plotted at the top, southward features at the bottom, and null observations (no feature) in the center. Observations at overlapping longitudes have been displaced vertically for clarity. Observations from 1980 are plotted above those from 1981. Solid lines connect data points corresponding to a continuous series of observations on a single night. A dashed line connects the points corresponding to two observations obtained ~3 hours apart on March 11 UT, 1981. The dotted line partially used for the data of April 13 UT, 1981, is meant only to call attention to the fact that during these observations Io passed through 0° magnetic longitude, and the plotted points therefore appear separated in the figure, as do the points for March 11 UT, 1981.

In addition to the review of the May 4, 5, 12 and 13 images summarized above, the remaining Region B/C images were reviewed by examination of glossy prints containing the D_1 and D_2 brightness images. The data quality and spatial morphology of these images were compared. Generally, the spatial morphology followed the picture established from the May data. It was also interesting to note that image sequences on May 13, June 14, May 6, and April 29, which have similar Io phase and Io System III magnetic longitude angles (see Figure 1), all exhibited the same peculiar changes in their spatial morphology that may indicate a time-dependent cloud interaction with possible longitudinal asymmetries in the Io plasma torus.

3. 1976-1979 Region B/C Images

Each of the 39 Region B/C images was recorded with an integration time of about 2 to 3 hours and hence provides a time-averaged picture of the sodium cloud over an Io phase angle interval of about 17° to 25° and an Io System III magnetic longitude of about 56° to 83°. Although these integration times are significantly longer than for the 1981 Region B/C images, the 1976-79 images still contain useful information for the intensity and spatial morphology of the cloud. The UT dates and time intervals for these 39 observations are given in Table 4. Also in Table 4 are the values of the geometric phase angle and System III magnetic longitude angle of Io for the start time and end time of each image. This angular information is also presented in graphical form in Figure 4.

In Figure 4, the angular coverage in system III magnetic longitude of Io is excellent, especially near eastern elongation. The angular coverage in Io geocentric phase angle is only deficient near 0° and 180° where observational conditions are poor because of the high background light levels reflected by Jupiter's disk. As can be seen in Figure 4, there is one pair of images where the coverage in both angles is essentially identical and there are many pairs of images that have nearly the same angular range. Intercomparison of these images and additional comparisons with images in the 1981 data set will help to establish the stability or variability of the sodium cloud over time scales of days, weeks, months and even one to four years. Two of the images were obtained on the encounter day (5 March 1979) of the Voyager 1 spacecraft with Jupiter, and several additional images were obtained within a week of this encounter date.

Table 4

1976-79 Io Sodium Cloud Image Data

	Date (UT)	UT Start	Io Phase	Io Sys III Mag. Longitude	UT End	Io Phase	Io Sys III Mag. Longitude
976	29 November	9:37	35.3	336.2	11:52	54.4	38.7
	3 December	2:58	73.5	299.3	6:28	103.4	36.4
	16 December	5:42	224.1	45.9	8:42	249.4	129.4
	18 December	6:58	281.6	335.5	9:58	306.8	59.1
977	18 February	3:07	263.5	182.3	5:17	281.7	242.6
	19 February	2:25	101.4	109.3	5:25	127.0	192.5
	26 February	2:30	85.6	100.5	5:10	108.3	174.5
	22 March	2:50	287.3	278.3	4:50	304.2	333.9
	4 December	8:10	35.0	142.6	11:10	60.3	226.1
	5 December	5:23	215.7	11.6	8:23	241.2	94.9
	5 December	8:35	242.9	100.4	11:35	268.4	183.8
	6 December	7:50	79.3	27.6	10:50	104.8	110.9
	11 December	9:23	30.6	165.9	12:23	56.0	249.4
	13 December	5:32	45.1	313.1	8:32	70.5	36.5
978	22 January	4:40	262.9	329.5	7:10	284.0	39.2
	22 January	7:20	285.4	43.8	8:50	298.0	85.6
	23 January	2:25	86.7	214.7	4:55	108.1	284.0
	17 February	2:45	138.2	338.4	4:45	155.3	33.9
	19 February	4:50	203.1	290.0	6:20	215.8	331.7
	19 February	6:25	216.5	334.1	7:55	229.2	15.8
	22 February	2:00	68.7	53.0	3:30	81.5	94.6
	22 February	4:09	87.1	112.7	6:09	104.1	168.1
	22 February	6:15	105.0	170.9	8:15	122.1	226.3
	24 February	2:03	116.4	308.0	4:03	133.5	3.5
	24 February	4:13	134.9	8.1	6:13	152.0	63.6
	15 December	9:30	203.2	67.8	12:30	228.8	150.9
	16 December	7:56	33.5	331.3	10:26	54.5	41.0
	16 December	10:34	55.6	44.7	13:04	76.7	114.3
979	26 February	3:00	251.5	341.3	5:30	272.7	50.8
	26 February	6:10	278.4	69.3	8:40	299.5	138.9
	26 February	8:50	300.9	143.6	11:20	321.9	213.2
	4 March	5:30	53.2	93.7	8:30	78.6	177.1
	5 March	4:04	245.5	360.0	6:34	266.6	69.5
	5 March	6:40	267.5	72.3	9:20	290.0	146.5
	6 March	3:03	79.5	279.6	4:13	89.4	312.0
	6 March	4:15	89.7	313.0	6:30	108.8	15.4
	7 March	4:34	296.6	268.0	7:04	317.7	337.7
	12 March	4:33	234.3	2.4	7:03	255.5	71.9
	12 March	9:00	271.9	126.1	11:30	293.0	195.7

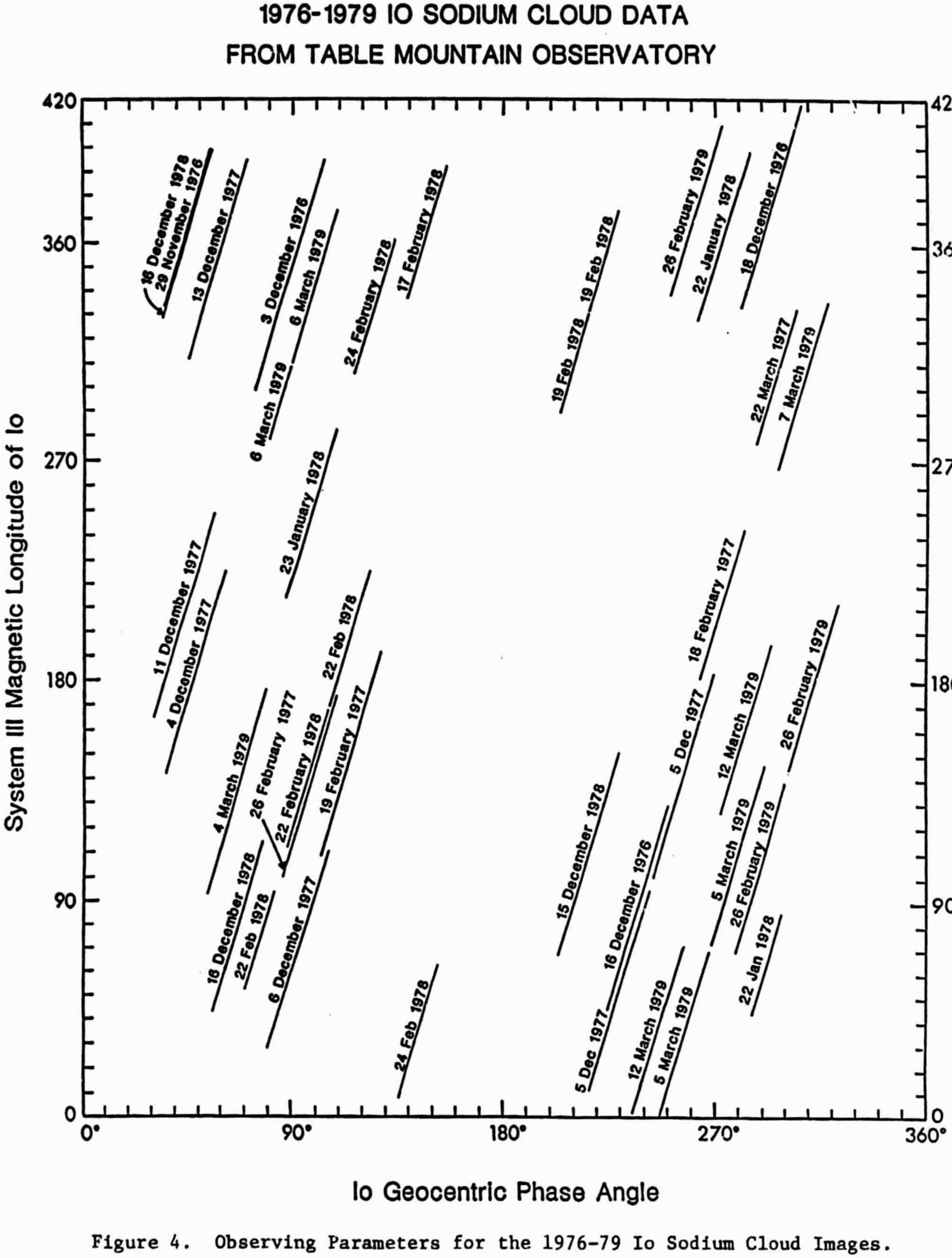

Figure 4. Observing Parameters for the 1976-79 Io Sodium Cloud Images.

The angular coverage for the Io geocentric phase angle and the System III magnetic longitude of Io over which each Region B/C image was recorded in the JPL Table Mountain Data Set is indicated.

Seven of the 1976-79 images were presented earlier in a paper by Goldberg et al. (1980). In this paper, a comparison was made between the first image recorded on March 5, 1979 and the second image recorded on December 5, 1977 (see Table 4). Both of these images have an Io phase angle at their recorded midpoints of 256°. In this comparison, the forward clouds were similar in length and brightness, but the trailing clouds were distinctly different and were not understood in the modeling analysis presented in the paper. The first image recorded on March 5 has a more developed trailing cloud which is distributed south of the orbit plane, while the second image on December 5 contained less sodium and has a trailing cloud that is distributed symmetrically about the orbit plane. From Figure 4, the explanation is now obvious, since it can be seen that the March 5 cloud is centered at a System III magnetic longitude of Io of 34.8° (i.e., in the south directional feature domain of Figure 3), while the December 5 cloud is centered at a System III magnetic longitude of Io of 142°(i.e., near the transition angle that separates the north and south directional features in Figure 3). This realization indicates that although the integration times of the 1976-79 images were long compared to the 1981 images, the earlier time-averaged images still have significant diagnostic value in understanding the structure and time variability or stability of the sodium cloud.

A brief review of data quality and the level of past processing of the 1976-79 images was undertaken by examination of glossy prints for a number of images showing the cloud either in a pixel brightness or a contour brightness format. Both image quality and level of processing varied tremendously over the data set. A more careful review of this data set will be required to pick candidate images for further image processing and study.

4. Slit Spectra Data

In addition to Region B/C image data reviewed above, significant amounts of slit spectra data were acquired in the 1974-1981 time period by the JPL Table Mountain Io sodium cloud observing program. The number of yearly measurements for both single slit (centered on Io) and multislit (two slits, nine arc seconds east and west of Io) observations acquired by this program are summarized in Table 5.

Single slit data obtained in 1974 and 1975 have already been published as noted in Table 5. These data were used to confirm resonance scattering as

Table 5

Summary of Io Sodium Cloud Slit Spectra

	Single Slit Data			Multislit Data	
Year	Number of Measurements	Slit Intensity	Published Reference	Number of Measurements	Published Reference
1974	64	averaged	1,2	-	-
1975	8	averaged	2	-	-
1976	11	1-D	-	4	3
1977	7	1-D	-	4	3
1978	4	1-D	-	1	3
1979	9	1-D	-	-	-
1980	-	-	-	-	-
1981	56	1-D	-	-	-

1. Bergstralh, J.T., Matson, D.L. and Johnson, T.V. (1975), Ap. J. (Letters), 195, L131.
2. Bergstralh, J.T., Young, J.W., Matson, D.L. and Johnson, T.V. (1977), Ap. J. (Letters), 211, L51.
3. Goldberg, B.A., Garneau, G.W. and Lavoie, S.K. (1984), Science, 226, 512.

the sodium D-line excitation mechanism and to first document the east-west intensity asymmetry of the sodium cloud. Single-slit data obtained in 1976-1979 and also in 1981, which have not yet been fully processed, provide in addition a spatial resolution along the slit length (not a slit averaged value as in the 1974 and 1975 data). This one-dimensional resolution will provide a more accurate assessment of the slit-averaged intensity, since the continuum light of Io's disk that is truncated by the narrow slit width under normal seeing conditions can more accurately be estimated in this case than in the case of the earlier 1974-1975 data. The single-slit data in the 1976-1981 time period will be valuable (1) as an absolute intensity calibration for the 1976-1981 image data, (2) as a means of expanding and extending the earlier analysis of the 1974 and 1975 data (Bergstralh et al., 1975, 1977), and (3) as a base for studying the stability/variability of the Io sodium cloud (and ulitmately the Io plasma torus) over the 1974-1981 time period.

The dates and times and the Io phase angle and Io system III magnetic longitude ranges associated with the single-slit spectra of 1976-1979 and 1981 are summarized in Table 6 and Table 7 respectively. Spectral data from 1976-1979, having exposure times between 30 and 60 minutes, were acquired at most three times per evening and were clustered with several nights scheduled per month. Collectively, this provides information for the brightness of the sodium cloud from a month to a several-year time scale. Spectral data for 1981, having exposure times of only a few minutes, were acquired only over six nights, but were obtained with many more observations per night. The 1981 data thus provide information for the brightness of the sodium cloud over a day to a month time scale and in this way are both complementary and overlapping with the 1976-1979 data.

Only a small number of multislit observations were acquired in the observing program as summarized in Table 5. These observations were used primarily, in conjunction with early image data, to provide a numerical measure of the spatial morphology of the forward cloud. This was accomplished by forming a ratio of the intensity of the cloud in one slit located nine arc seconds to the west of Io to the intensity of the cloud in the other slit located nine arc seconds east of Io. This information has been recently reported by Goldberg, Garneau and LaVoie (1984) and was earlier used together with image data to first document the east-west orbital asymmetry in the Io sodium cloud (Goldberg et al., 1978). For completeness, the dates and times

Table 6

1976-1979 Io Sodium Cloud Single Slit Spectra

	Date (UT)	UT Start	Io Phase	Io Sys III Mag. Longitude	UT End	Io Phase	Io Sys III Mag. Longitude
1976	29 November	7:28	17.1	276.5	8:28	25.5	304.3
	3 December	1:47	63.4	266.5	2:47	71.9	294.3
	3 December	9:47	131.8	128.3	10:47	140.3	156.1
	4 December	1:35	265.8	207.4	2:35	274.3	235.3
	4 December	2:42	275.3	238.5	3:42	283.7	266.4
	10 December	1:38	47.3	251.6	2:38	55.8	279.3
	10 December	2:40	56.1	280.2	3:40	64.6	308.0
	16 December	2:39	198.3	321.1	3:09	202.5	335.0
	25 December	3:11	234.7	219.1	4:11	243.1	247.0
	25 December	8:35	280.2	9.5	9:05	284.4	23.5
	25 December	9:13	285.5	27.2	9:43	289.7	41.1
1977	19 February	5:28	127.4	193.9	5:58	131.6	207.8
	5 October	12:30	99.4	197.6	13:10	105.1	216.2
	13 October	8:25	253.3	20.1	9:25	261.8	47.9
	5 December	11:46	269.9	188.9	12:46	278.4	216.8
	6 December	10:58	105.9	114.6	11:58	114.5	142.3
	13 December	8:42	72.0	41.1	9:42	80.5	68.9
	14 December	5:30	249.4	258.3	6:30	257.8	286.1
1978	22 January	3:46	255.3	304.5	4:16	259.5	318.4
	22 February	3:34	82.1	96.5	4:04	86.3	110.4
	15 December	12:40	230.3	155.6	13:40	238.8	183.3
	16 December	6:38	22.5	295.1	7:38	30.9	323.0
1979	26 February	5:36	273.6	53.6	6:06	277.8	67.5
	4 March	2:48	30.3	18.6	3:48	38.8	46.4
	4 March	8:44	80.6	183.6	9:44	89.1	211.4
	5 March	2:20	230.7	311.8	3:05	237.1	332.7
	5 March	9:24	290.6	148.3	10:09	296.9	169.2
	6 March	6:37	109.8	18.6	7:07	114.1	32.5
	7 March	3:41	289.2	243.4	4:26	295.5	264.3
	12 March	3:39	226.6	337.4	4:24	233.0	358.3
	12 March	7:09	256.3	74.7	7:54	262.6	95.5

Table 7

1981 Io Sodium Cloud Single Slit Spectra

Date (UT)	UT Start	Io Phase	Io Sys III Mag. Longitude	UT End	Io Phase	Io Sys III Mag. Longitude	Number of Measurements
25 March	6:11	17.9	251.5	6:29	20.4	259.8	4
25 March	9:05	42.4	332.2	9:13	43.5	335.9	2
25 March	9:23	44.9	340.6	9:42	47.6	349.4	4
25 March	10:31	54.4	12.1	10:36	55.1	14.5	2
5 April	4:41	84.4	347.8	5:09	88.4	0.8	7(slit E-W)
5 April	9:04	121.4	109.8	10:03	129.7	137.2	17
6 April	4:03	283.0	276.8	4:26	286.3	287.5	3
6 April	8:07	317.7	29.7	8:37	322.0	43.6	5
11 April	3:49	218.6	6.0	4:27	224.0	23.5	5
27 April	4:00	237.7	243.2	4:17	240.2	251.0	3
4 June	6:20	70.5	94.3	6:37	72.9	102.2	4

and the range of Io phase angles and Io system III magnetic longitudes covered by the multislit data are summarized in Table 8.

5. 1981 Region A Images

The 153 images of the brightness near Io were obtained during eight nights using short exposure times and no satellite occulting mask. The UT dates and time intervals for these observations are given in Table 9. Also included in Table 9 are the values of the geocentric phase angles and System III magnetic longitude of Io for the start and end times of each evening. As can be seen by comparison of Table 3 and Table 9, these Region A images were obtained over the same time period as the 1981 Region B/C images.

A very preliminary review of data quality shows that images vary from poor to good. Atmospheric seeing and difficulties encountered in removing the continuum reflected from Io, hinder in determining brightness morphology of the cloud very near Io. For one of these images (Goldberg, Garneau and LaVoie, 1984), the brightness averaged over a five arc second diameter disk centered on Io compares favorably with the earlier 1974-1976 averaged brightness values of Bergstralh et al. (1975, 1977) obtained by a 3 x 8 arc second rectangular slit centered on the satellite. Additional comparisons of this type are useful in exploring the stability or variability of the sodium cloud over the 1974-1981 time period. Such comparisons will necessarily require additional data processing to be undertaken.

Table 8

1976-1978 Io Sodium Cloud Multislit Spectra

	Date (UT)	UT Start	Io Phase	Io Sys III Mag. Longitude	UT End	Io Phase	Io Sys III Mag. Longitude
1976	30 November	7:40	223.3	228.2	10:40	248.6	311.6
	1 December	4:41	40.7	93.1	7:41	66.2	176.4
	3 December	6:44	105.7	43.8	9:41	131.3	127.0
	25 December	5:20	252.8	279.0	7:50	273.9	348.6
1977	18 January	1:55	67.7	352.2	4:55	93.3	75.4
	25 January	2:12	54.2	349.1	5:12	79.8	72.3
	8 February	2:53	27.7	346.0	4:23	40.5	27.6
	27 February	2:36	289.1	51.0	5:21	312.3	127.5
1978	22 January	1:41	237.7	246.5	3:41	254.6	302.2

Table 9

1981 Region A Images: Observing Chronology†

Date of Observations	Start Conditions: Time (UT)	Start Conditions: Io Phase Angle (deg)	Start Conditions: Magnetic Longitude of Io‡ (deg)	End Conditions: Time (UT)	End Conditions: Io Phase Angle (deg)	End Conditions: Magnetic Longitude of Io‡ (deg)
25 March	8:36	38.3	318.8	8:43	39.3	322.0
5 April	7:57	111.9	78.8	8:14	114.3	86.6
6 April	6:16	301.9	338.3	6:23	302.9	341.6
11 April	4:55	228.0	36.5	6:14	239.3	73.0
	6:41	243.1	85.5	7:50	253.0	117.3
	8:14	256.4	128.4	8:57	262.5	148.3
12 April	4:19	66.7	326.7	4:42	69.9	337.4
	5:08	73.5	349.4	10:10	115.9	129.6
	10:40	120.2	143.5	10:44	120.7	145.4
13 April	3:00	259.2	237.2	5:24	279.7	303.6
27 April	4:47	244.4	264.9	5:53	253.8	295.4
	6:12	256.6	304.2	6:54	262.5	323.6
	7:10	264.8	331.0	8:38	277.3	11.7
	8:48	278.8	16.3	9:03	280.9	23.2
4 June	6:06	68.6	87.8	6:10	69.1	89.7

†Image exposure times are typically 2 1/2-5 minutes, depending primarily on the intensifier gain setting.

‡System III (1965)

III. Data Processing Activities

As a result of the above review and assessment, data processing priorities have been identified, and a specific plan of action has been developed and initiated in the first year. Significant effort has been expended in successfully implementing this plan at the Multimission Image Processing Laboratory (MIPL) of the Jet Propulsion Laboratory. Data processing priorities and their implementation at MIPL are discussed below.

1. Data Processing Priorities

The three main data processing priorities are summarized in Table 10. The first priority is vital and a prerequisite for modeling studies of the spatial morphology of the cloud. The second prioirity is necessary for determining the source rate of sodium from Io and in studying its temporal behavior. The third priority applies in a systematic manner the results of the first two priorities to specific data chosen in the modeling analysis studies.

2. Data Processing Plan

The plan developed, adopted and initiated at MIPL to performing the data processing priorities is summarized in Table 11. The implementation of this plan at MIPL has been somewhat slower than expected, but was unavoidable because of the recent (fall 1984 - spring 1985) major reorganization of the MIPL facilities which entailed their old IBM 360 computer being replaced by two new VAX 11/780 computers and all data processing software being appropriately converted. Because of this, a significant amount of effort had to be expended in establishing the necessary software and personnel base at MIPL to accomplish the data processing requirements of this project. By mid February, an excellent personnel base for this project had been established at MIPL. Susan K. LaVoie, recently promoted to group supervisor at MIPL, is the key staff person responsible for overseeing this data processing. Additional senior data processing expertise is being provided by Glenn W. Garneau. Both G. Garneau and S. LaVoie have made significant contributions to past processing of the Io sodium cloud data at JPL (see Goldberg, Garneau, and LaVoie, 1984) and hence are very well suited for this project. In addition to G. Garneau and S. LaVoie, less senior MIPL staff personnel will also be assigned

Table 10

Data Processing Priorities

1. Improve Techniques to Remove Distortion in the Brightness Distribution of Images

   a. Implement improved background subtraction techniques for images.

   b. Improve techniques for removal of image distortion near Io produced by continuum light scattered by Io.

2. Determine the Absolute Brightness Calibration for the Images

   a. Analyze 1981 1-D slit data on Io's disk and Region A image data to establish an absolute brightness calibration for the 1981 data.

   b. Analyze 1976-79 1-D slit data on Io's disk to establish a brightness calibration for the 1976-79 data.

3. Prepare Images for Modeling Analysis

   a. Using improved techniques in 1 above, remove brightness morphology distortions in a selected subset of images.

   b. Using the information in 2 above, absolutely calibrate this selected subset of images.

Table 11

Summary of Io Sodium Cloud Data Processing to be Performed by MIPL

I. Provide Access to Image Data and Single Slit Data in Raw Form

   (a) Convert TTRAN for VAX 11/780 to reformat data tapes

   (b) Convert VLOGSIP for VAX 11/780 to format data for VICAR programs

   (c) Collect all tapes containing image and slit data

II. Refine Procedure for Removing Various Image Background Signals

   (a) Provide VICAR programs (programs to filter, interpolate, plot, contour, remove parts of frames, provide registration of parts of frames, subtract frames, normalize frames, rotate frames)

   (b) Remove Io spectrum from image (most difficult task)

      (1) locate and align wavelength of absorption feature in the frame

      (2) use spectrum from another satellite to model and subtract off Io reflectance spectrum.

   (c) Remove Jupiter background (relatively straightforward)

   (d) Define and remove optimally the background read-out (photon) noise level of each frame (i.e., average frames / use optimal low pass filter / use Fourier transform techniques)

III. Process Specified Images for Removal of Background Signals

IV. Process Single Slit Data for Calibration Purposes

   (a) Instrumental calibration

   (b) Removal of sky background

   (c) Produce integrated intensity profile

to support this project as required. To insure maximum science returns in the data processing activities, all MIPL staff personnel associated with this project will work together with and under the direct supervision of Bruce A. Goldberg of JPL.

The first step in Table 11 was essentially accomplished in the third quarter of this project year. The conversion of the software programs, required specifically for reformatting the Io sodium cloud data, was performed by MIPL without cost to this project. This conversion has removed the primary bottleneck that had up to that point prevented any of the subsequent data processing steps from being performed. The second step, that of refining the procedures for removing various image background signals, requires the joint involvement of senior MIPL staff and B. Goldberg. This second step was initiated in mid February. These refinement procedures are required to improve early developed techniques so as to display more accurately the true nature of the spatial morphology of the image data for modeling studies. The second step was completed and the third step was just initiated by the end of this first project year. Significant amounts of effort were expended in successfully developing and refining the procedures in the second step. The third step will be continued and the fourth step initiated in the second project year. Both the third and fourth steps may be accomplished with the participation of experienced but less senior MIPL personnel working together with B. Goldberg. The first completely refined 1981 Region B/C images will be available for modeling studies early in the second project year.

IV. Formulation and Initiation of Modeling Activities

1. Modeling Priorities

With the knowledge gained in the review and assessment of the data sets (section II), modeling analysis priorities have been established and are summarized in Table 12. Implementation of these modeling objectives has been somewhat tempered by the large effort expended in reviewing and preparing the data (see Sections II and III). Nevertheless, progress in several areas has been made and is discussed below.

The first modeling analysis priority in Table 12 was accomplished in the second quarter of this project year. This is important because in virtually all images of the sodium cloud, the north-south spin axis of Jupiter was aligned along the spectral direction of the instrument so that different doppler motion along the line of sight produces differing amounts of north-south displacements on the detector. For small velocity differences (~few km sec^{-1}), these distortions are small, but for larger velocity differences (~10-100 km sec^{-1}) such as are produced by any fast sodium ejected from Io, these displacements are sufficient to distort the complete north-south spatial morphology of the cloud. The modified model properly calculates the D-line intensities on the sky plane both including and excluding these distortions so that proper comparison can be made with the JPL data as well as with other non-spectrally-displaced sodium image data. These displacements may in fact be helpful in understanding the velocity structure in the cloud.

For the second modeling analysis priority in Table 12, preliminary modeling calculations were performed for comparison with selected Region B/C images. Although the detail comparison must be postponed until further data processing is applied to the images, the initial comparison suggests a sodium source rate for the forward cloud (Region B) of between 1-2 x 10^{26} atoms sec^{-1} and a sodium source rate of approximately one half this value for the directional features outside of Io's orbit. These values are similar to the sodium source rates determined by Pilcher et al. (1984). Additional model calculations were also performed for a dispersion of initial ejections speeds (2.6, 20, 30, 40, 56.8 and 75 km sec^{-1}) from Io and for ejection of sodium from different regions of the satellite exobase. These model calculated images were then roughly compared with the 1981 region B/C images (which need further processing) in order to ascertain the importance of higher components of the

Table 12

Modeling Analysis Priorities

1. Include the north-south spatial distortions in the model calculated D_2 images introduced by the instrument because of the doppler motion of the sodium atoms along the line of sight.

2. Study the spatial characteristics of the sodium directional features in the 1981 data.

3. Study the east-west differences in the cloud morphology and relate them to solar radiation pressure, sodium source characteristics, and sodium sink characteristics.

4. Study east-west intensity differences in the 1981 cloud data and relate them to solar radiation pressure, sodium source characteristics, and sodium sink characteristics.

5. Study the temporal variability/stability of the cloud images having similar Io phase and/or System III magnetic longitudes of Io.

6. Study "other structural features" identified in the images.

sodium ejection velocity in the data. These comparisons indicated that most of the sodium visible in Region C is ejected for velocities of 20 km sec^{-1} or less, although a small amount of sodium may well be present (but is not dominant) for higher velocity components.

Only preliminary modeling activities have been undertaken for the modeling analysis priorities 3-6 of Table 12. One of these preliminary activites has been to correlate and classify the different Region B/C images by their Io phase angle ϕ and Io System III magnetic longitude angle ψ in four ways: (1) for consecutive image studies (i.e., $\phi(t)$, $\psi(t)$), (2) for east-west studies (i.e., $\phi_w = \phi_E + 180°$ and $\psi_E \approx \psi_w$ or $\psi_E \neq \psi_w$), (3) for cloud stability studies, $(\phi_1, \psi_1) \approx (\phi_2, \psi_2)$, and (4) for System III dependence studies $\phi_1 = \phi_2$, $\psi_1 \neq \psi_2$. These classifications are necessary to identify specific images (or image sequences) of sufficient quality to support the modeling studies. Another preliminary activity has been to examine images to identify "other structural features" that may be valuable in studying the source and sink characteristics of the cloud. Quantitative modeling of selected Region B/C images will begin early in the second year as reprocessed data becomes available to support these studies.

2. Lifetime for Sodium Atoms in the Plasma Torus

The lifetime description ad^pted for sodium atoms in the Io sodium cloud model was improved in the third quarter. Improvements were made in the electron temperature and density by incorporating unpublished results obtained from new analyses of both the Voyager 1 PLS electron data (Sittler, 1984) and ion data (Bagenal, 1984). Corrections for a hotter ion temperature as discussed by Bagenal et al. (1984) as well as unpublished ion abundances (Shemansky, 1984) were also used in determining the distribution of electrons along magnetic field lines above and below the centrifugal equator of the plasma torus.

This new lifetime for sodium, assuming longitudinal symmetry in the plasma torus, is shown in Figure 5. Inside of a radial distance of 8 R_J, the new lifetime is similar to earlier derived values in magnitude and structure. The new lifetime values on the centrifugal equator are, however, slightly larger and fall off slightly less rapidly with displacement from the equator than the old values. This occurs because of the lower electron temperatures between 6 and 8 R_J and the higher ion temperatures (everywhere)

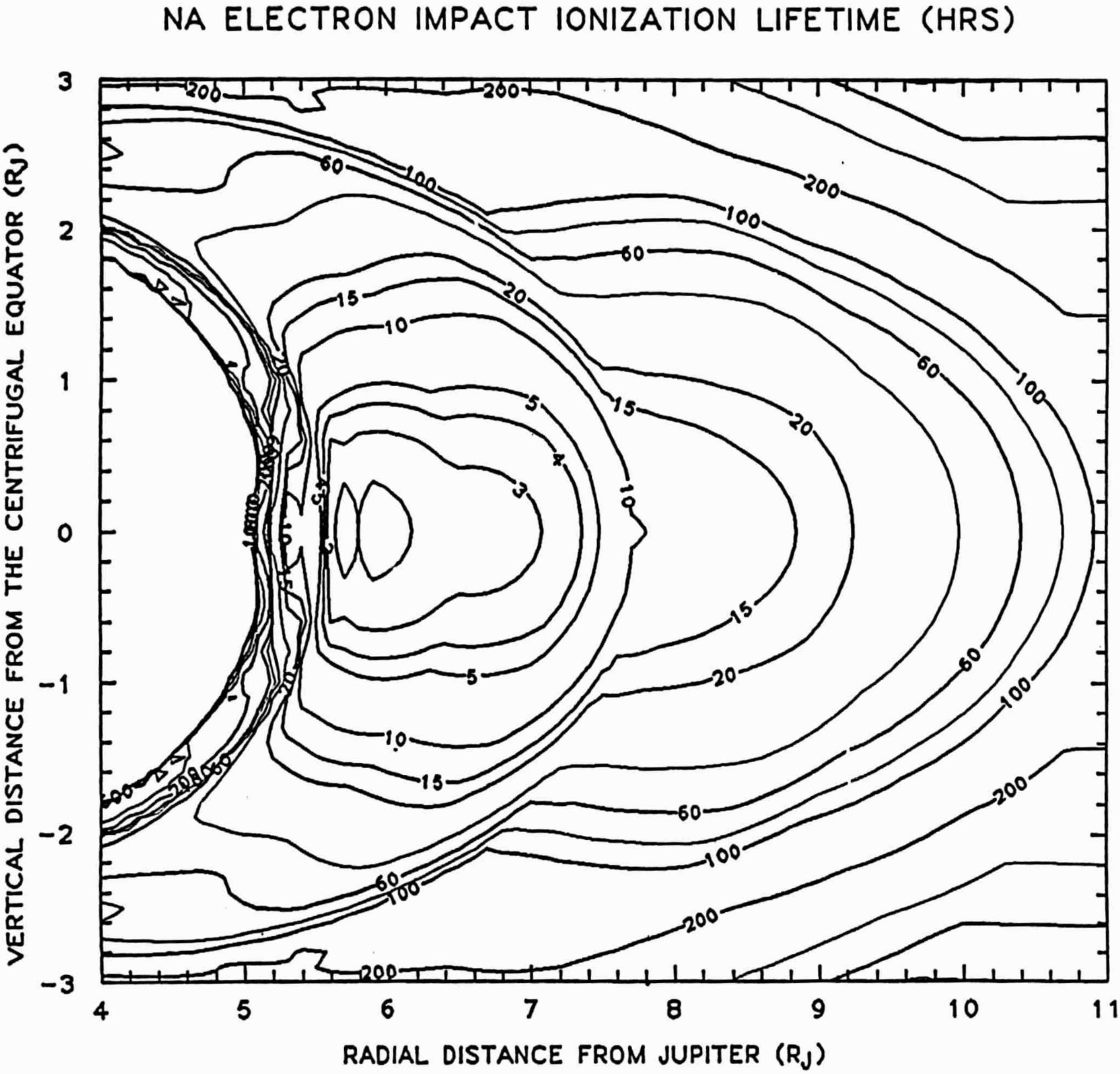

Figure 5. Lifetime of Sodium Atoms in the Plasma Torus.

The improved lifetime description is calculated by using the most recently available properties for the ions and electrons deduced from Voyager 1 encounter data as discussed in the text.

adopted in the new torus description. Outside of a radial distance of about 8 R_J, the new lifetime in Figure 5 exhibits an extension both radially and vertically that was not as pronounced in the older lifetime descriptions. This enhanced extension results from the higher ion temperature and also from a higher electron density and electron temperature that now occur in the new description outside of about 8 R_J. Further refinements are expected in the sodium lifetime when new ion abundance information is available from the reanalysis of Voyager UVS data using a new improved atomic data set for oxygen and sulfur (Shemansky, 1985).

The sodium lifetime in Figure 5 represents the best picture for the Voyager 1 encounter in 1979. In the fourth quarter of this project year, possible changes of the plasma conditions that might have occurred between the 1979 encounter date and the dates of the sodium observations in 1981 were reviewed by examination of two papers (Pilcher, Fertel and Morgan, 1985; Morgan, 1985) describing the plasma torus. Additional plasma data for 1981 as well as for 1976-1979 remain to be examined in the second year to aid in determining the nature of any substantial changes that occurred in this time period.

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